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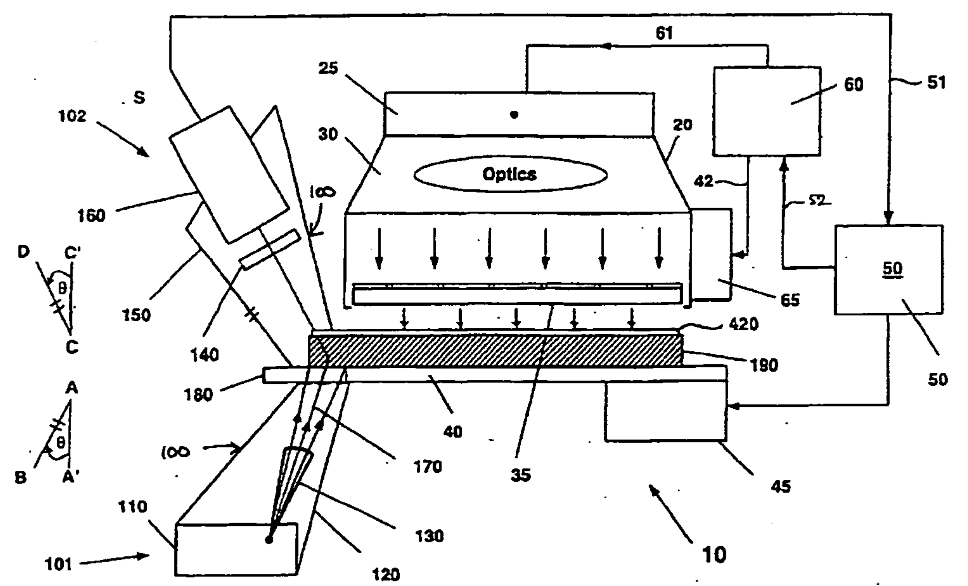
(54) Title: MANUFACTURE OF OPTICAL DEVICES



(57) Abstract: A method of manufacturing an optical device using a stepper photolithographic process, in which the device is defined on the surface of wafer substrate (420) using a plurality of image fields which are "stitched" together during the stepper process to define the device wherein stitched together image fields (709, 710) overlap, the over lapping areas (711) of the respective image fields being tapered so as to minimise optical losses.

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MANUFACTURE OF OPTICAL DEVICES

Field

This invention relates to the manufacture of optical devices and in particular, but not exclusively to devices made from large semiconductor wafers.

Background of the Invention

Semiconductor devices are typically manufactured in processes in which a semiconductor substrate undergoes a series of deposition cycles during which further semi-conductor materials, metals or insulators are deposited. These layers may undergo various photolithographic stages that delineate the required features, and these features are subsequently defined by wet or dry etching processes. Typically a large number of discrete semiconductor devices may be formed on a single wafer and once formed these are separated by dicing or cleaving operations. The individual devices are then available for further processing.

Improvements in technology have increased the size of wafers from about 50mm up to 200mm, and even larger wafers of 300mm have been developed in silicon. In semiconductor production the single crystal wafers are of a particular crystallographic orientation. For silicon and III-V wafers the preferred orientations are chosen to facilitate wet or dry etching where depending upon orientation the etch rate can be highly anisotropic.

In the field of opto-electronic device fabrication where devices are made from semiconductors such as GaAs or Si, the processes may require accurate alignment relative to the crystal planes. It is common in opto-electronic devices to utilise crystal

planes to form smooth cleaved facets acting as mirror surfaces for laser cavities and input/output facets of integrated waveguide devices e.g. modulators. For cleaving to be effective as a means of generating mirror surfaces the cleave line must be parallel to or at a predefined angle to specific features of the device and thus there is a requirement for accurate alignment of the device relative to the crystal planes.

A problem faced in opto-electronics manufacture is that an optical device such as a GaAs modulator can be 30mm in length or longer and this has manufacturing implications when it is necessary to cleave a wafer for forming individual components. If a device is not accurately aligned to the crystal planes of the wafer then the cleaved edge may divert from the edge of the device and if the packing density of individual devices per wafer is high, then the cleaved edge may intersect with a neighbouring device. To prevent this occurrence the density of devices per wafer would have to be reduced.

Conventionally, smaller semiconductor wafers, of 100mm dia. or less, are supplied with ground and polished flats at the edge of the wafer which are aligned to a particular crystal plane. Larger semiconductor wafers are supplied with alignment notches formed in the edges.

The photolithographic apparatus mechanically registers the alignment features and aligns the lithographic pattern for the devices with the underlying crystal planes typically within an accuracy of 0.5 degrees of arc. This degree of accuracy may arise because a typical accuracy of alignment of a notch or flat is about ± 0.5 degrees and the detection apparatus of a lithographic machine may align to the flat or notch with an

accuracy of ± 0.1 degrees. This degree of accuracy is unacceptable for larger opto-electronic devices and high packing density of small devices.

One solution is to cleave a precision edge at the start of the process, however such cleaved edges make wafers prone to breakage during processing and precludes the use of many types of automated equipment which cannot handle incomplete wafers. For larger wafers the cleave makes the wafer unstable during spinning of a resist in the photolithographic process. Also since a cleaved edge is not bevelled it distorts the resist profile leading to poor contact and resolution during a contact printing process.

Problems can also arise in the alignment of adjacent imaging fields produced by a stepper giving rise to discontinuities or defects at the interface therebetween.

There are two main causes of this. Firstly, there can be physical misalignment of the photolithographic mask, light source and its optics, and the photoresist covered wafer, relative to each other. Secondly, when using projection optics with an image stitcher (or even an ordinary mask aligner), there are optical aberrations created by the lenses and other optical components used in the projection. Misalignment is a particularly serious problem, and one which is more likely to occur and to be of a more serious nature, in larger devices. Consequently, this is of particular relevance to the production of optoelectronic devices, such as modulators, which are commonly of such a size that they require image stitching.

With an increase in the size of wafers above 100mm then problems arise due to the lithographic process itself. It becomes harder to maintain line width resolution over the

entire wafer. With devices having dimensions of several centimetres it also becomes difficult to use standard contact or proximity photolithographic techniques.

GB-A-2356786 describes a process in which the lithographic pattern on a mask is accurately aligned with the crystal planes of a wafer using X-ray diffraction.

Object of the present Invention

The present invention provides improved methods of manufacture of large opto-electronic devices on a wafer by photolithographic techniques

Statements of Invention

According to a first aspect of the invention there is provided a method of manufacturing optical devices using a stepper photolithographic process, in which at least one device is defined on the surface of a substrate using a plurality of image fields which are stitched together during the stepper process to define said device wherein adjacent stitched together image fields overlap, the over lapping areas of the respective image fields being profiled so as to minimise optical losses.

According to a second aspect of the invention there is provided a method of manufacturing optical devices from wafers using a stepper photolithographic process in which at least one device is fabricated by defining at least one component layer in a resist layer on a semiconductor wafer by a step-and-repeat process wherein the stepper apparatus utilizes registration marks located on the wafer to indicate the orientation of the crystal planes.

The term optical devices includes opto-electronic devices made from semiconductor materials, optical and opto-electronic devices made from non-semiconductor materials such as lithium niobate, and electro-optic polymers.

Preferably at least one device is defined on at least one resist layer on the surface of the wafer by a plurality of image fields. The image fields may be formed on a single lithographic mask, sometimes called a reticule, or on a plurality of masks. The image fields are stitched together during the stepper process to produce a complete image field for a single layer of the device being fabricated, wherein the device geometry exceeds the image field size of the stepper apparatus.

Where devices are defined by a plurality of layers, each layer may be defined by one or more masks each formed with one or more image fields.

Preferably the stepper apparatus aligns itself to registration marks previously placed on the wafer to accurately indicate the orientation of the crystal planes.

Preferably the orientations of the crystal planes are determined using X-ray diffraction techniques by passing the X-ray radiation through the wafer or reflecting the radiation from a surface of the wafer.

After placement of the registration marks by photolithography and subsequent processing, the wafer is subsequently transferred to the stepper (sometimes called step & repeat) photolithographic process which utilises the registration marks to orientate the wafer relative to the print image.

The devices are typically fabricated from multiple layers of the wafer, and each mask, or set of masks is used to form a specific layer of the device. Within each layer the adjacent images are aligned with a high degree of precision, such that there is optical continuity along the device, using a method called image field stitching.

When the image fields of multiple mask sets overlap, and respective portions of devices defined by the masks also overlap, and respective portions of devices defined by said mask sets also overlap, the overlapping images of said portions are designed to reduce optical loss mechanisms such as light scatter in the resultant device.

Apparatus for the alignment of a print mask relative to the orientation of the crystal planes of a wafer is disclosed in GB-A-2356786. For the purposes of the present invention the lithographic print mask is adapted to print registration marks which are usable by a stepper apparatus.

The present invention provides for the manufacture of optical devices from a plurality of stitched together optical images.

According to the present invention there is also provided an optical device made by a method according to the first and second aspects of the present invention.

Yet another aspect of the invention provides a wafer having a resist layer with an optical device defined therein by a plurality of overlapping stitched together photolithographic image sets.

A further aspect provides a optical device formed from a wafer, wherein the device comprises a plurality of stitched together portions.

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Description of the Drawings

The invention will be described by way of example and with reference to the accompanying drawings in which:

Figure 1 is schematic view of apparatus for placing registration marks on a semiconductor wafer in accordance with one aspect of the present invention,

Figure 2 is a representation of a stepper apparatus registration mark,

Figure 3 is an illustration of image field stitching,

Figure 4 is a schematic representation of mask pattern designs,

Figure 5 is a schematic drawing of a step-and repeat apparatus, and

Figures 6 and 7 show further schematic representations of mask pattern designs.

Detailed Description of the Invention

With reference to Fig.1 there is shown an apparatus 10 for use in a method according to a preferred form of the invention. The apparatus 10, with suitable alternative apparatus, and their operation are disclosed on GB-A-2356786 but will be described herein to provide an understanding of the present invention. Such apparatus can handle large wafers of 150mm or more including wafers up to 300mm.

The apparatus 10 comprises a conventional lithographic tool 20, an X-ray diffraction apparatus 100, a wafer support, or chuck, 40 and controls 50 and 60.

The lithographic tool 20 includes a radiation source 25, an optical unit 30 and a lithographic mask 35 having a lithographic pattern thereon. The optical unit 30 collimates the radiation from the source 25 which passes through the mask 35 and onto the organic resist layer 420 coating the exposed side of a wafer 190. The mask 35 may be moved by a mask actuator 65 which controls the angular rotation of the mask.

The wafer chuck 40 has a slot 180 therein over which a portion of a wafer 190 may be located and is linked to an actuator 45 which is connected via control path 41 to the wafer alignment control unit 50. The control unit 50 includes programmable means and operates the actuator 45 for angular rotation of the chuck 40 in response to signals received from the X-ray diffraction apparatus 100 through control path 51. The control unit 50 may also be manually controlled by an operator for orientation of the chuck 45.

The control unit 50 is connected to the lithography control unit 60 via control path 52. The control unit 60 is connected to the radiation source 25 through control path 61 and to the mask actuator 65 via control path 42. The control unit 60 controls the radiation emission and the orientation of the mask.

The X-ray diffraction apparatus 100 comprises an X-ray emitter 101 located beneath the chuck 40, and detector 102 located above the chuck 40. The X-ray emitter 101 comprises a shield 120 with a point X-ray source 110 and a collimator 130 located within the shield 120. The shield 120 extends to the underside of the chuck 40 and shields the chuck 40, the wafer 190 and human operators from stray radiation. The

source 110 is a 35 kV water cooled commercial X-ray source which may include a copper target and which is operable to emit predominantly X-ray radiation at a wavelength of 0.154nm although radiation of other wavelengths may also be emitted. The collimator 130 may be made from brass or other metal, and forms an X-ray beam 170 having a maximum semi-angle greater than the cut-off angle of any wafer to be loaded on the chuck 40 such that at least some of the X-ray directed towards the wafer 190 are at an angle that can be Bragg diffracted.

The detector 102 comprises a shield 150 which encloses a beam discriminator 140, and part of a detector unit 160. The shield 150 extends from the detector unit 160 to the upper side of the chuck 40. The discriminator 140 uses a four-bounce channel cut crystal which exhibits a high transmission factor and high sensitivity to beam direction. The discriminator 140 also functions as a monochromator to remove unwanted X-ray components away from 0.154nm wavelength. The detector unit 160 is connected to the control unit 50 through the control path 51.

For a GaAs wafer 190, it is preferred that the angle θ subtended by the X-rays from a normal A-A or C-C to the major plane of the wafer should be in the order of 20-25 degrees for a first order diffraction. This angle θ will change depending upon the chosen wafer material. A beam 170 of X-ray radiation predominately at 0.154nm propagates through the slot 180 in the chuck 40 and through an edge portion of a semiconductor wafer 190 on the chuck. The X-ray beam 170 is diffracted (in accordance with Braggs Law) and collected through the discriminator 140 and detector unit 160. The detector unit generates an output signal S in the form of a series of pulses corresponding to X-ray photons and which is used by control 50 for controlling

the orientation of the wafer 190 relative to the X-ray beam. The diffraction apparatus is aligned relative to the chuck 40 to collect radiation diffracted from a preferred crystal plane of the wafer.

The apparatus 10 is initially calibrated to set the mask 35 for angular alignment relative to a test wafer whose crystal planes are known. After calibration, a production wafer 190 is loaded onto the chuck 40 and X-rays are propagated through the wafer as before. The control unit 50 monitors the signal S and instructs the actuator 45 to orientate the wafer until a maximum signal is detected at which point crystal planes within the wafer 190 are aligned to an acceptance angle of the discriminator 140. The alignment control 50 then generated a signal A to the lithography control unit 60 which activates the lithographic tool 20 to print thereby transferring the mask feature, that is the registration mark(s), to the exposed organic resist coating 420 on the wafer 190.

Fig. 2 shows a wafer 190 with lines 701, 702 representing the underlying crystal planes. A plurality of registration marks 703 are positioned with reference to those planes and after exposure the wafer 190 is removed from the chuck 40 and the resist layer developed in an appropriate solvent. The resulting pattern is used in a subsequent process to transfer the registration marks to the wafer. The registration marks 703 are then usable for further processing in stepper apparatus.

The registration marks 703 transferred from the mask 35 onto the wafer resist layer are utilised for the subsequent lithographic process in a step-and-repeat photolithographic apparatus represented schematically in Fig. 5. Fig. 5 illustrates a reduction step-and-repeat apparatus. The image field is stepped over the wafer

surface by two dimensional translation of the wafer whilst the photolithographic mask M is held stationary. After exposure of one device site on the wafer, the wafer is moved to the next device site and the process repeated. The translation stage accurately moves a wafer with respect to the imaging optics and exposes adjacent new areas of the wafer surface. An example of a suitable apparatus is the PAS 5500/60 manufactured by ASML which is accurate to a resolution of 0.45 microns and alignment accuracy of 70nm.

Referring now to Fig. 3, an optical device is fabricated by defining the device image on several layers of a wafer, one layer at a time. Once the image is defined on a resist layer a fabrication process such as etching, deposition etc. is carried out. Once the process is completed the resist layer is removed. A new resist layer is spun down and the next layer of the device is defined. This process is repeated until the device is completed. The registration marks are located on ground zero and protected from the process steps for the different multiple layers.

When the device is large, a layer image may not fit within a mask and the stepper process uses the registration marks to enable a semiconductor device 712 to be formed by image field stitching of sections of the device using different image fields 713,714,715. The example device requires three passes of the stepper over the wafer. The machine vision system of the stepper locates the registration marks 703 and allows very accurate alignment of an image field and the wafer. A first image field 713 is exposed onto a resist surface of the wafer and its mask then removed and a second mask for a second image field 714 installed. The stepper then aligns the second image 714 very accurately with the initial image field 713, that is within an accuracy of 70nm.

The two image fields 713,714 are precisely aligned before the second exposure occurs. A third mask for a third image field 715 is then installed in the stepper following the same procedure.

In an alternative procedure a plurality of image fields, in this example three, may be placed on a single mask and each image is exposed singly.

The mask patterns 713-715 are designed so as to prevent defects occurring in a device where the patterns for the device 712 align. Such defects will act as a source of optical discontinuity. Different interfaces between adjacent patterns are shown in Fig. 4.

Case 1 represents a butt joint between two images 704 and 705. Since the stepper can align images only with 70nm accuracy this joint may cause some discontinuity and is not a preferred arrangement.

Case 2 represents an overlap joint 707 between two images 706 and 708 in say for example a waveguide. A misalignment of such joints may result in a bulge in the pattern at the point of intersection, the bulge arising due to double exposure of the photoresist where the image fields overlap.

Case 3 represents the preferred joint 711 between overlapping images 709 and 710. The overlapping areas are shaped, e.g. tapered, to reduce the possibility of forming a bulge in the joint, and so help minimise optical losses in the device defined by the images.

Once a waveguide has been delineated in the resist layer 420, the layer 420 is developed and the wafer passed on to a suitable process e.g. etching, deposition etc.

The photolithographic technique may use a 'positive' photoresist, which is characterised in that the areas that are exposed to light (through the transparent areas of the corresponding mask) are removed during development. Metal (or other material) is then evaporated to coat the resultant surface, coating the remaining resist and the exposed wafer alike. The remaining resist is then removed, which takes with it the metal that was deposited on top of it, and leaving behind the metal that was deposited directly onto the exposed areas of the wafer. This resultant pattern of metal on the wafer's surface is then used as a protective etch-mask whilst the surrounding areas are chemically etched.

It would also be possible to use a photolithographic technique using negative resist.

As mentioned above, when two exposures are made onto a region of photoresist, the edges of the post-development pattern that are defined by those areas of double exposure will bulge slightly (into the unexposed areas) with respect to those areas that are defined by only a single exposure. Thus, when the positive resist is developed, the resistless areas, which are created where the exposure took place, will bulge outwards slightly, i.e. be slightly wider, with respect to the singly exposed areas.

The resist pattern that is developed from an area that has received a single exposure

is slightly wider than would be expected from linear optics, du to diffraction and scattering of the light. This results in a slight increase in the area that is exposed, with the extent being limited to areas where the resist has received adequate light to expose it. In the event of double exposure, this effect is repeated, and so the unintentionally exposed areas receive more light, which results in the regions that receive adequate light being larger – consequently these areas bulge with respect to the singly exposed areas. This bulging is typically of the order of 100nm.

The alignment accuracy of a stepper is typically better (i.e. smaller) than 100nm, eg around 70nm. Typical dimensions of the tapered ends of the mask features are around 20 microns in length and 4 microns in width. Thus, the aspect ratio of the sides of the tapers (2 microns width of one side of the taper : 20 microns length) is 1:10. The angles of the tapers are thus typically of the order of 6 degrees.

Figures 6 and 7 are further schematic representations of mask pattern designs (the features thereof being exaggerated and not to scale).

Fig. 6 shows a schematic representation of pairs of exposures created by conventional square-ended mask features, and resultant outlines of the photoresist after development, in the cases of various relative misalignments of the pairs of exposures.

Case 1 represents a perfectly aligned butt joint between two (square-ended) images 800, 802. Such exposures could theoretically lead to a perfectly straight-sided post-development resist pattern (a parallel strip removed, with positive resist).

However, in practice, square cornered mask patterns give rise to slightly rounded corners in the corresponding post-development resist patterns. Consequently, even if it were possible to align the two exposures to form a perfect butt joint, there would be resultant slight indentations (not shown) at positions 806, 807 to the post-development photoresistless area.

Further, however, the accuracy of alignment that is necessary to achieve this effect is difficult to achieve in practice, and the following cases represent three examples of typical consequences of misalignment.

Case 2 represents a gap misalignment of images 810, 812. The consequences of a gap which results from this form of misalignment are extremely serious for an optoelectronic device. Hence, to avoid the risk of this misalignment occurring, it is preferred to seek a deliberate overlap between square ended mask features. As with Case 1, the corners of the developed patterns 813, 815 would be slightly rounded (not shown in Fig. 6, Case 2).

Case 3 represents an overlap misalignment of images 820, 822, creating an area of double exposure 821. The consequence of this double exposure is that edges of the post-development photoresistless area in the area of double exposure 824 bulge with respect to the sides of the post-development photoresistless areas in the areas of single exposure 823, 825.

The end features of the regions of bulging edges of the post-development

photoresistless areas may be relatively short, and with small radii of curvature 826, 827, 828, 829. The outline of the central photoresistless areas causes comparable features to occur in the optoelectronic device that is subsequently processed. These short regions 826, 827, 828, 829 of high curvature in the sides of the device cause serious loss and scattering of light transmitted along the optoelectronic device.

Case 4 represents a lateral misalignment of overlapping images 830, 832. The consequences of this misalignment are sharp, step-like edges 836, 837 to the post-exposure photoresistless area. The outline of the photoresistless areas causes comparable features to occur in the optoelectronic device that is subsequently processed. Such step-like edges in the optoelectronic device cause serious loss and scattering of light transmitted along the optoelectronic device. As before, the corners of the developed patterns would be slightly rounded (not shown in Fig. 6, Case 4).

Fig. 7 is a schematic representation of pairs of exposures using tapered ended mask features, and resultant outlines of the photoresist after development, in the cases of various relative misalignments of the pairs of exposures.

Case 1 represents a perfectly aligned joint between two (taper-ended) images 900, 902, creating an area of double exposure 901. The consequence of this double exposure is that edges of the post-development photoresist in the area 904 of double exposure will slightly bulge with respect to the sides of the post-development photoresist in the areas of single exposure 903, 905.

However, due to the tapered features' large aspect ratio (their long length relative to

their width), the bulge caused by this overlap region will result in only large radii unevenness of the edges of the resultant optoelectronic device (i.e. very gentle curving – no sharpness as with the bulging created by overlapping square-ended exposures). Such large radii features have less serious consequences for the light transmitted along the optoelectronic device.

Case 2 represents a gap misalignment between two images 910, 912, creating an area of double exposure 911. As a result of the gap, the sides of the exposed region taper slightly to a waist 916. The resultant waist 914, 917 that is created in the post-development photoresistless area is slightly smaller than that of the images, due to the bulging of the doubly exposed area 911.

As before, due to the large aspect ratio of the tapers, the resultant unevenness of the edges of the resultant optoelectronic device does not have serious consequences for light transmission therethrough.

Case 3 represents an overlap misalignment between two images 920, 922, creating an area of double exposure 921. This region of double exposure creates a bulging of the sides of the post-development photoresistless area. However, due to the large aspect ratio of the tapers, the resultant unevenness of the edges of the resultant optoelectronic device does not have serious consequences for light transmission through the device.

Case 4 represents a lateral misalignment of images 930, 932, creating an area of double exposure 931. The consequence of this misalignment is slightly angled sides

936, 937 to the post-development photoresist. However, due to the large aspect ratio of the tapers, the resultant angling of these edges 936, 937 relative to those of the two adjoining portions 933, 935 is small. Consequently this angling does not have serious consequences for the resultant optoelectronic device's light transmission properties.

The contrasting effects of lateral misalignment of overlapping images that are formed from those that are nominally square ended Fig.6 Case 4, and those that are tapered Fig.7 Case 4 is apparent. The tapered case gives rise to a minimal reduction in the resultant optoelectronic device's light transmission properties, in contrast to the square ended case in which there can be serious loss and scattering of the light.

The tapered areas may be straight-sided as shown but other tapering forms may be used.

The above method provides for the fabrication of large complex optical devices and circuits on wafers, particularly semiconductor wafers, with the devices accurately aligned with the crystal planes of the wafers without need for ground or cleaved flats on wafers.

CLAIMS

1. A method of manufacturing optical devices using a stepper photolithographic process, in which at least one device is defined on the surface of a substrate using a plurality of image fields which are stitched together during the stepper process to define said device wherein adjacent stitched together image fields overlap, the over lapping areas of the respective image fields being profiled so as to minimise optical losses.

2. A method as claimed in Claim 1, in which at least one image field may be formed on each of a plurality of lithographic masks.

3. A method as claimed in Claim 1 or Claim 2 in which a plurality of image fields are formed on at least one lithographic mask.

4. A method as claimed in any one of Claims 1 to 3 in which registration marks for the stepper process are placed on the wafer using a photolithographic process in which a mask is aligned relative to crystal planes in the wafer using Bragg diffraction techniques.

5. A method according to any one of Claims 1 to 4 in which the overlapping areas of the respective image fields have a tapered form.

6. A method of manufacturing optical devices from wafers using a stepper photolithographic process in which at least one device is fabricated by defining at least

one component layer in a resist layer on a semiconductor wafer by a step-and-repeat process wherein the stepper apparatus utilizes registration marks located on the wafer to indicate the orientation of the crystal planes.

7. A method according to Claim 6 in which at least one device is defined on at least one resist layer of the wafer by a plurality of image fields which are stitched together during the stepper process.

8. An optical device formed by a method as claimed in any one of Claims 1 to 7.

9. A wafer having a resist layer with an optical device defined thereon by a plurality of overlapping stitched together photolithographic image fields from at least one mask formed by a method as claimed in any one of claims 1 to 7.

10. An optical device formed from a wafer, wherein the device is defined by a plurality of stitched together portions by a method as claimed in any one of claims 1 to 7

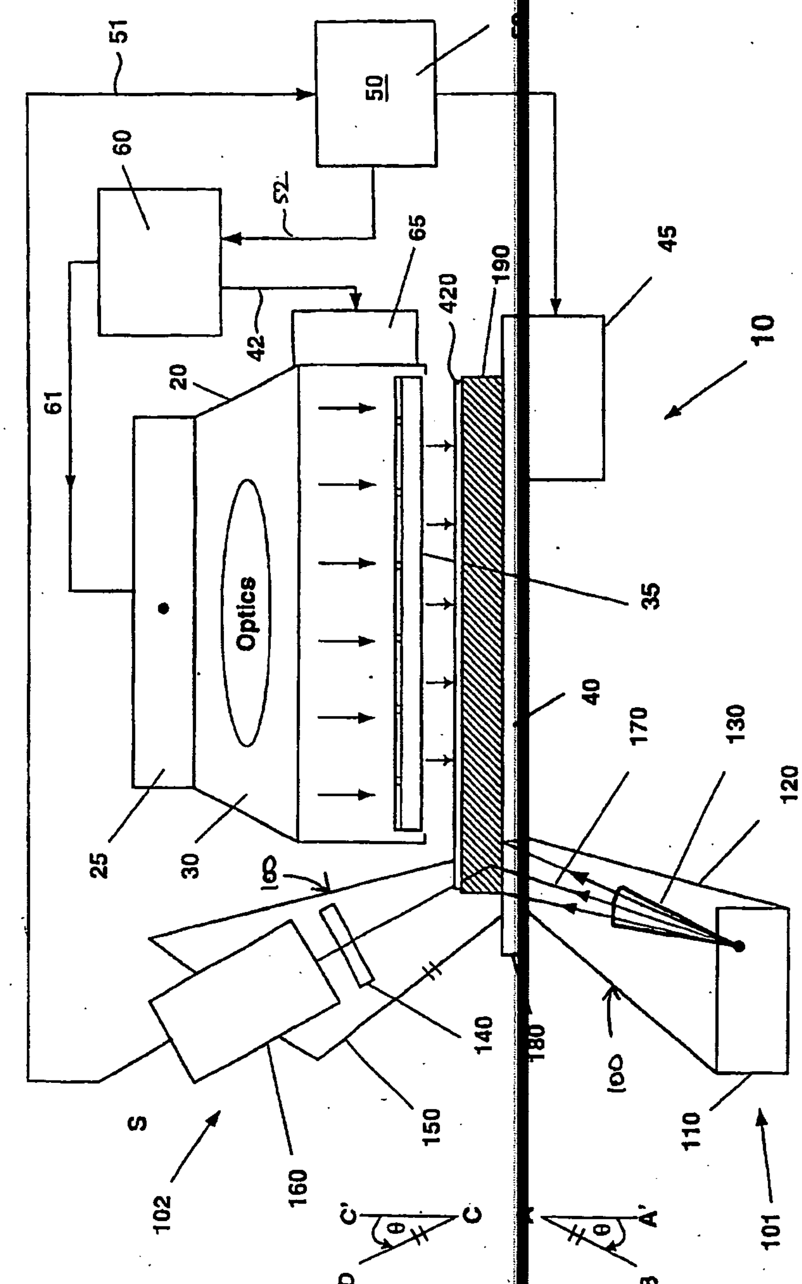
Optics
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Figure 1

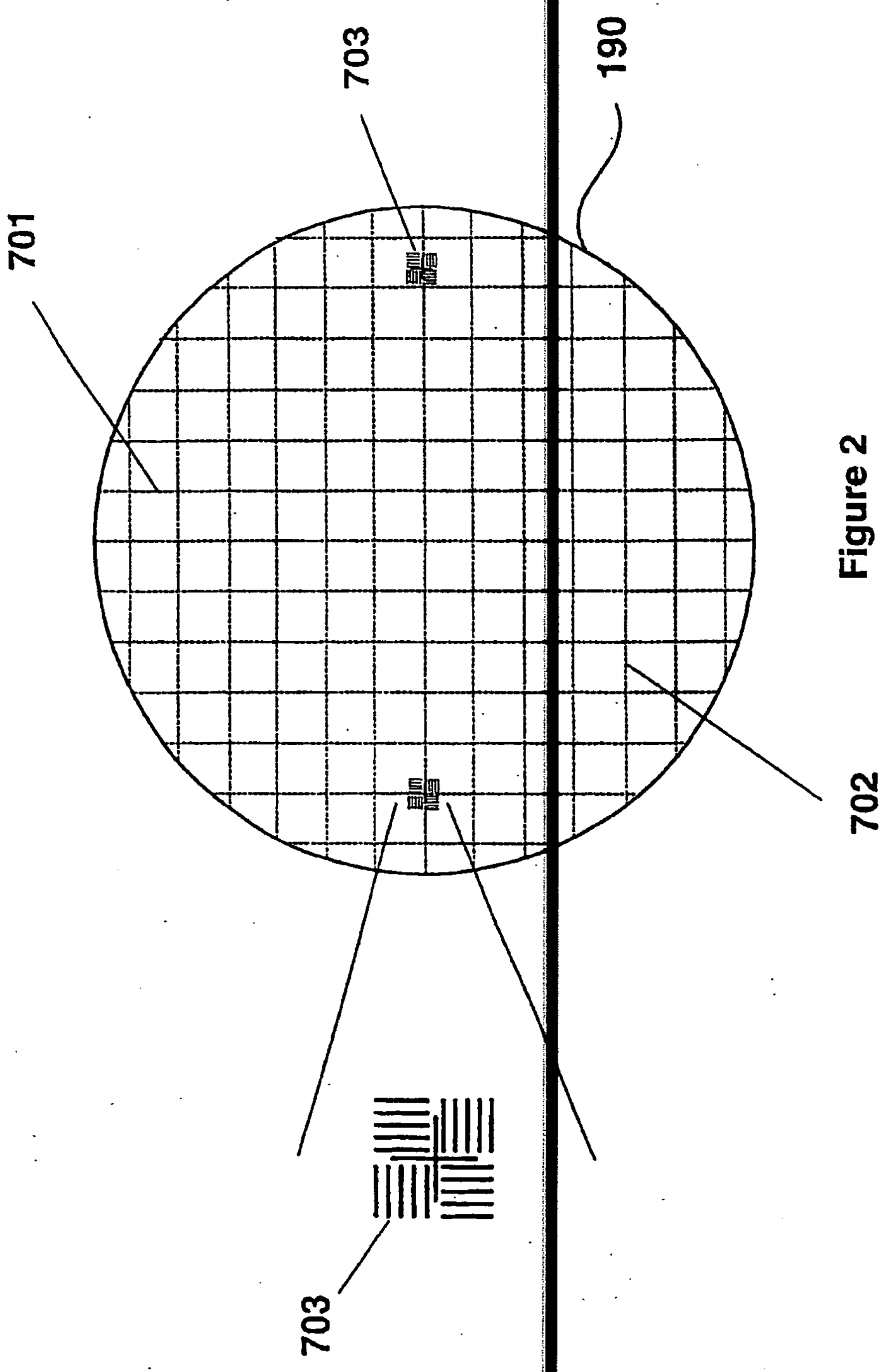


Figure 2

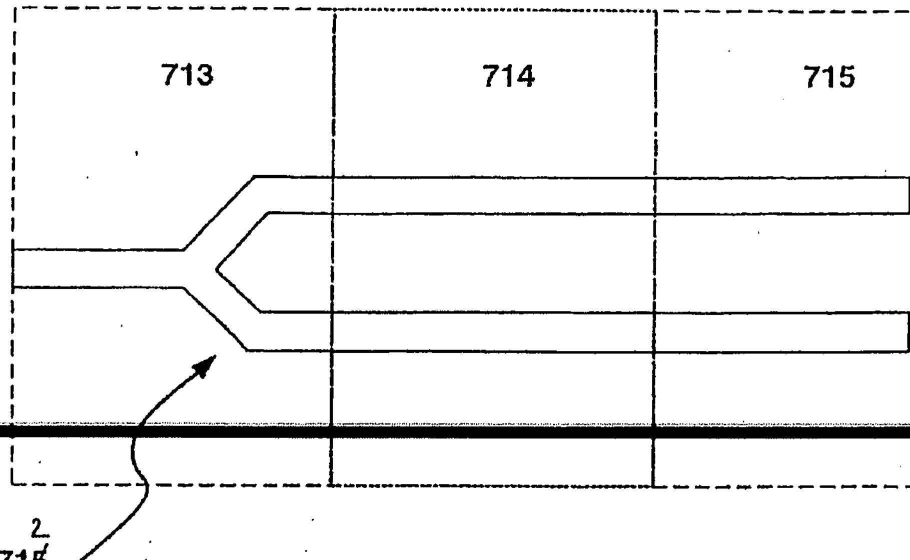


Figure 3

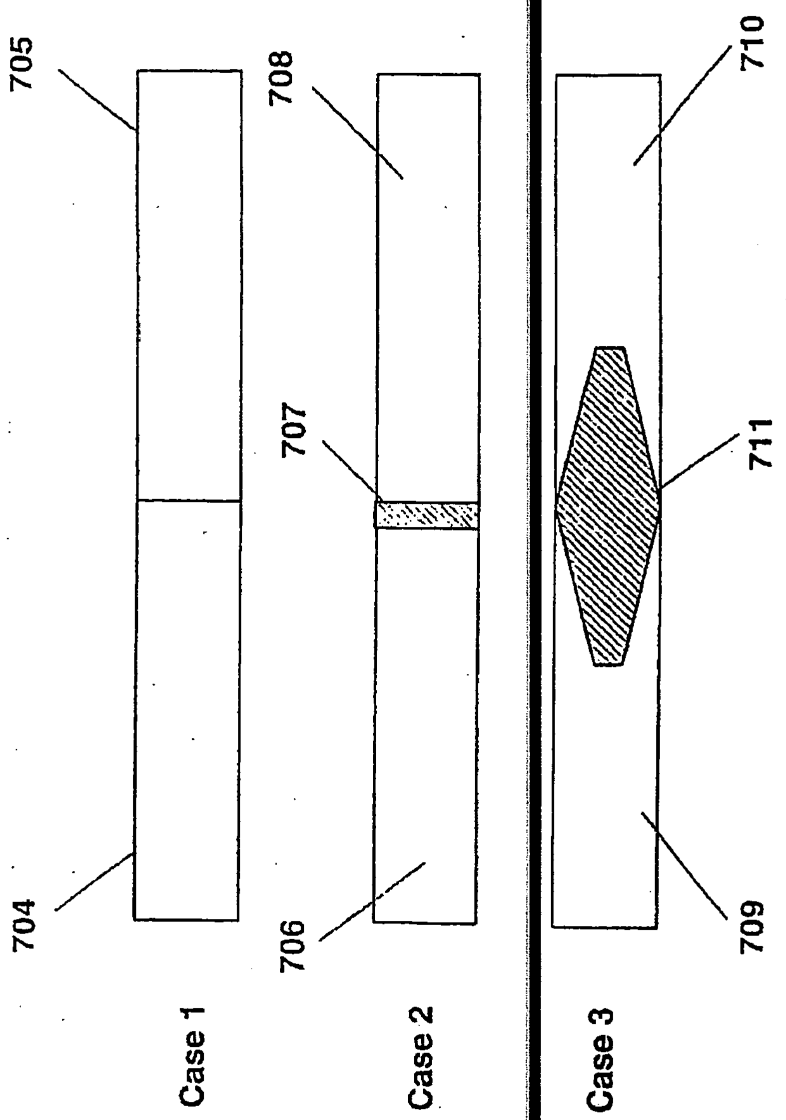


Figure 4

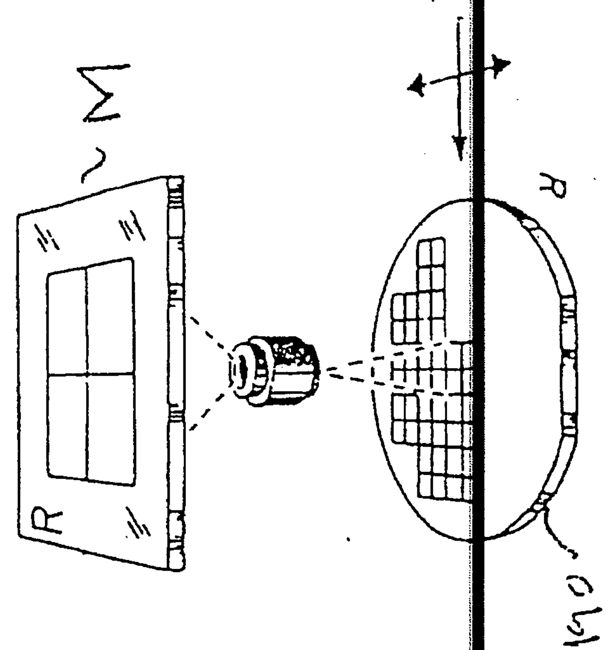
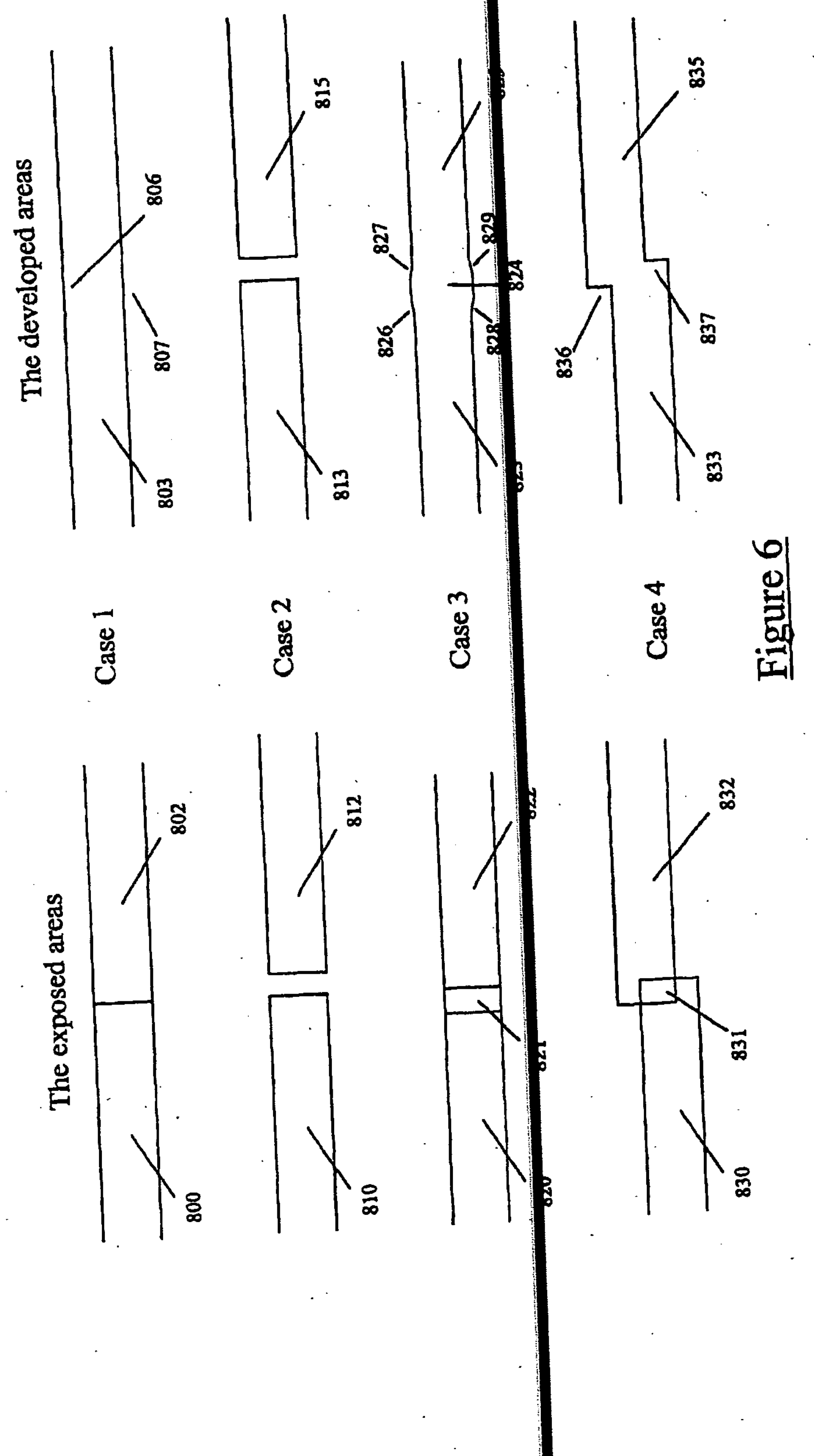


Figure 5


The developed areas
The exposed areas
Case 1
Case 2
Case 3
Case 4
800
802
803
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807
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Figure 6

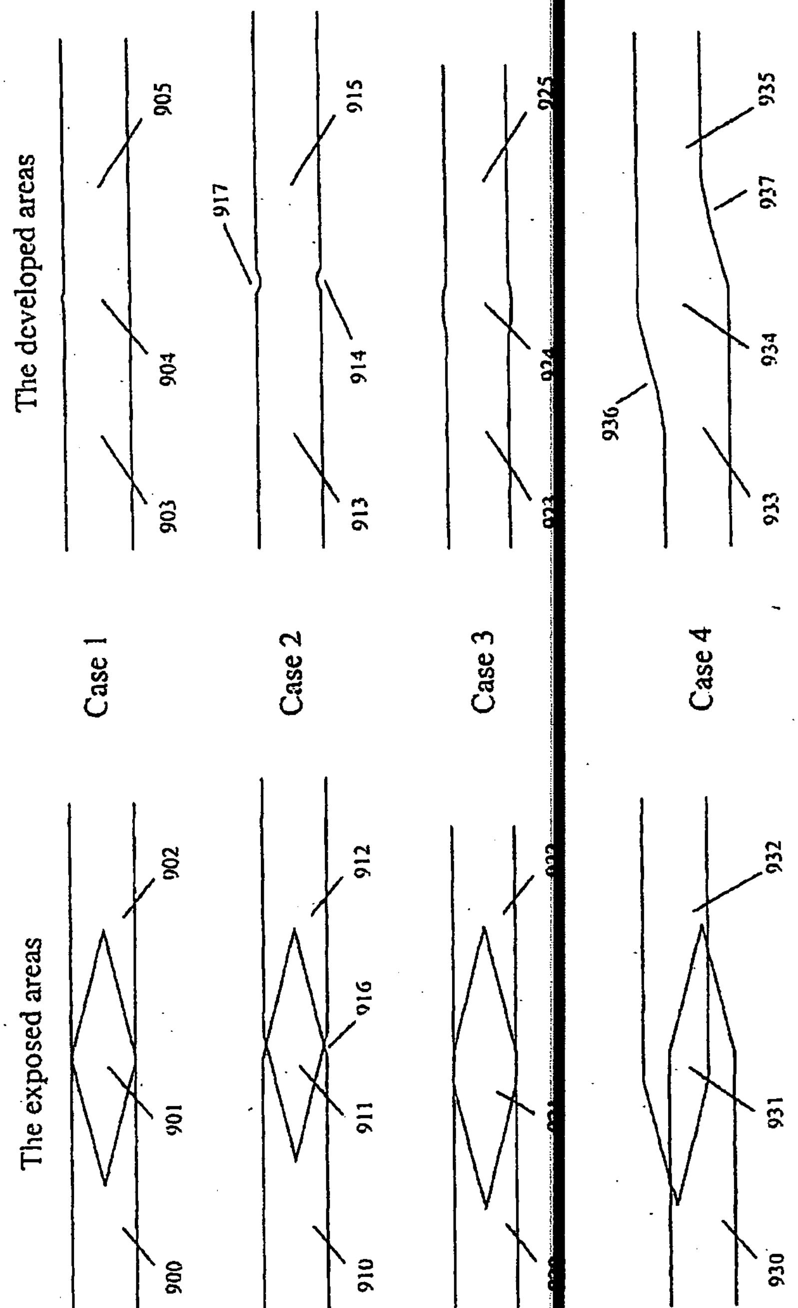
The developed areas
The exposed areas
Case 1
Case 2
Case 3
Case 4
900
901
902
903
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Figure 7